

# The Cosmological Revolution

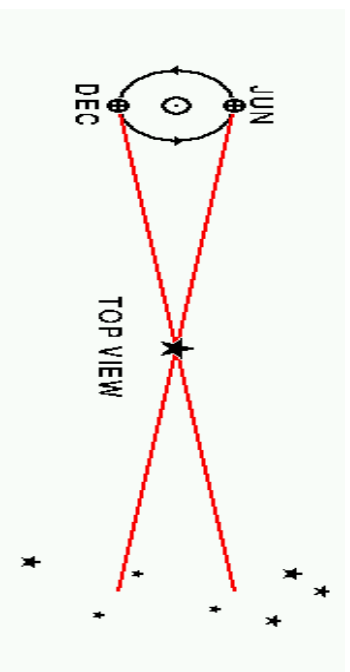
## Cosmology: The Science of the Evolution and Structure of the Universe ( Shorter Oxford Dictionary)

Katrin Heitmann, Theoretical Division, LANL

Picture of the M78 Nebula Taken by the Sloan Digital Sky Survey

## Astronomical Units

Distance Measure: Parsec



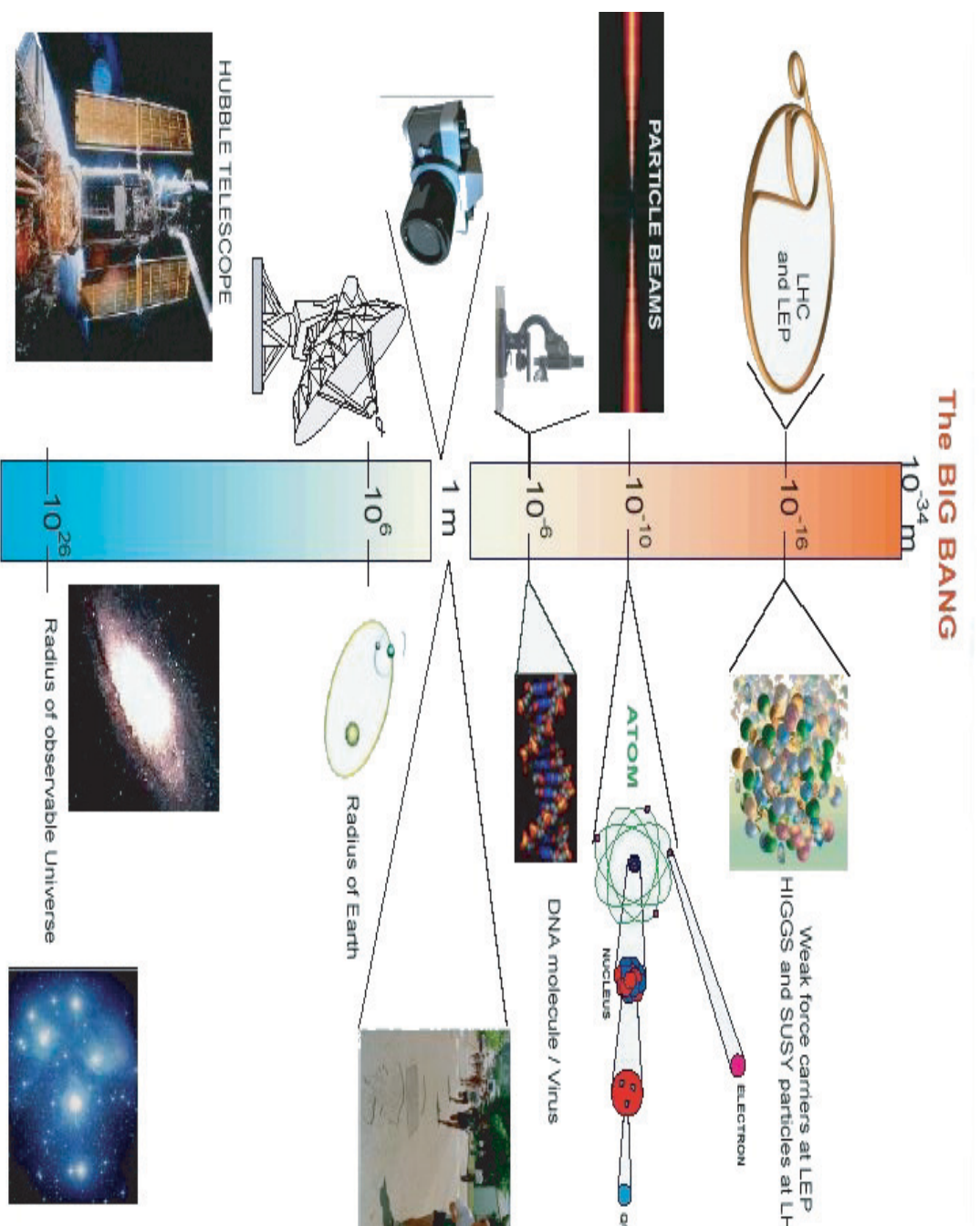
- $1 \text{ pc} \approx 3.086 \times 10^{13} \text{ km} \approx 3.26 \text{ light years}$ ,  $1,000,000 \text{ pc} = 1 \text{ Mpc}$ 
  - Separation of Stars in a Galaxy  $\approx 1 \text{ pc}$
  - Separation of Bright Galaxies  $\approx 1 \text{ Mpc}$
  - Size of the Observable Universe:  $\approx 4500 \text{ Mpc}$

Velocity Measure: km/s

- Typical Velocities of Galaxies: Hundreds of km/s

Mass Measure: Solar Mass

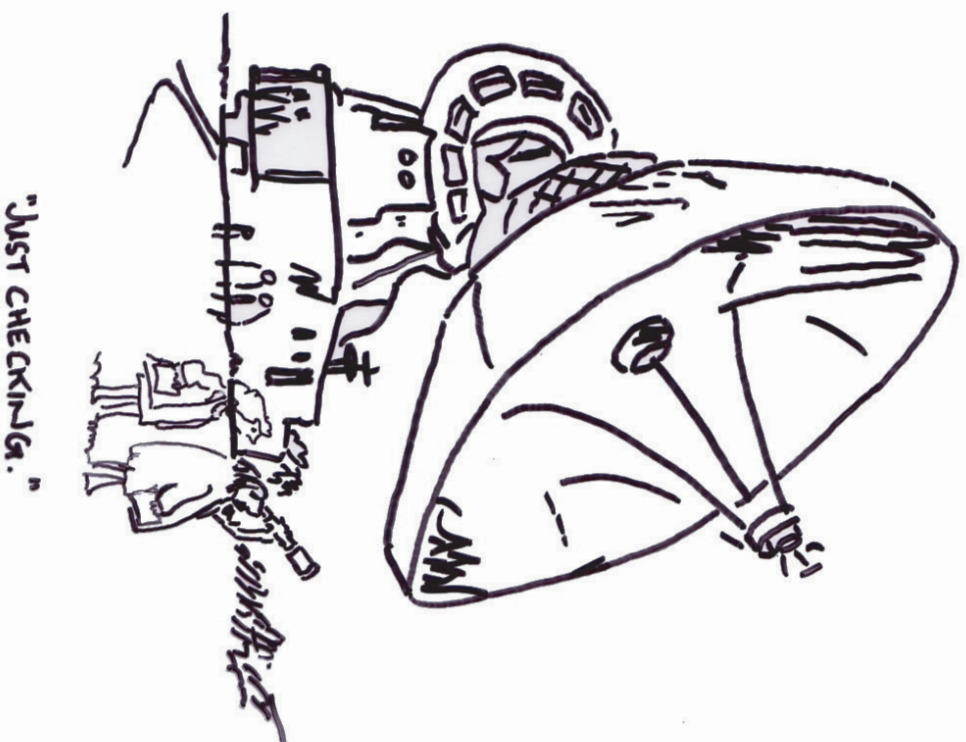
- $1 M_{\odot} \approx 1.99 \times 10^{30} \text{ kg}$ , Typical Galaxy  $\approx 10^{11} M_{\odot}$



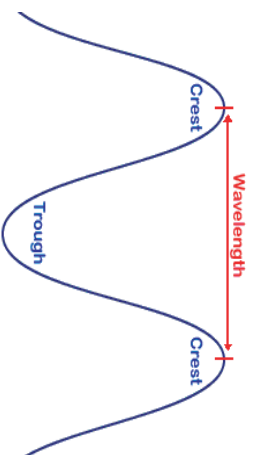
## Questions...

- How Big is the Universe?
- What is the Geometry of the Universe?
  - How Old is the Universe?
  - What is the Universe Made of?
- How are the Constituents Distributed?
- What is the History of the Universe?

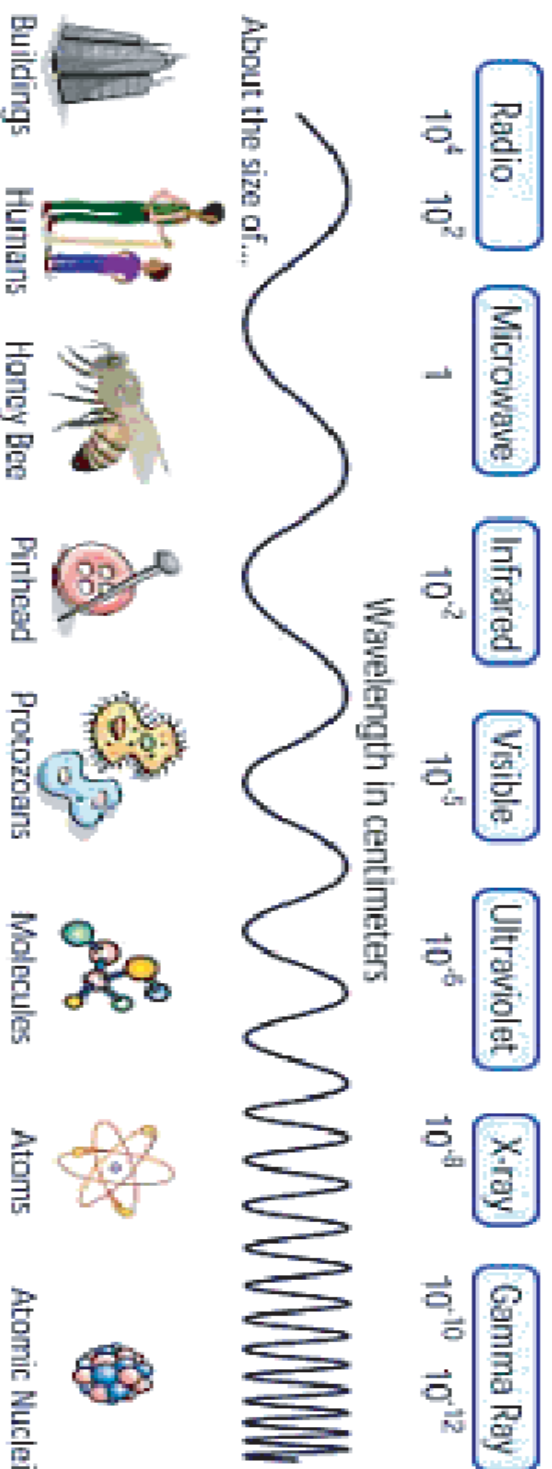
## Observations



## Observations: Photons



### The Electromagnetic Spectrum



# The Universe at Different Wavelengths

... and Theory

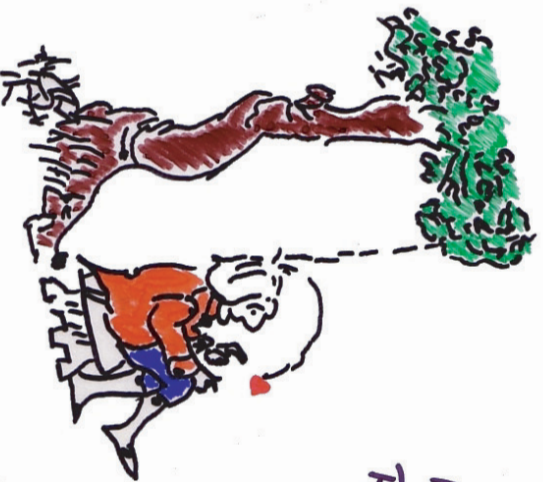
QUANTUM  
MECHANICS

PARTICLE  
PHYSICS

NUCLEAR  
PHYSICS

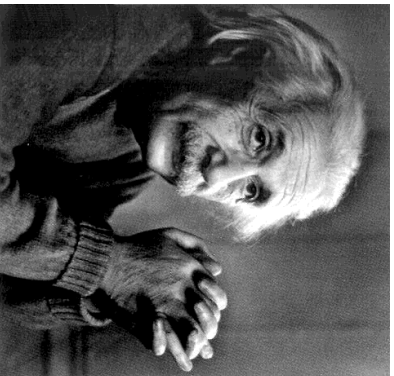
PLASMA  
PHYSICS

GENERAL  
RELATIVITY





## Main Theoretical Ingredient : General Relativity



1915: Einstein Develops General Relativity

Prediction: All of Space is **Dynamic**,  
either Contracting or Expanding

Einstein Puzzled!

Hubble, Astronomer at the Lowell Observatory,

Measures Spectra of Nebulae

Finds them to be **Redshifted**

⇒ Nebulae are moving away from Earth!

## The Cosmological Redshift

- Distance between Us and Galaxies is **increasing**
- Reason: Creation of Space → General Relativity

⇒ Wavelength Gets Stretched!

⇒ Measured Light from Distant Galaxies is Redshifted!



## The Universe is Expanding!

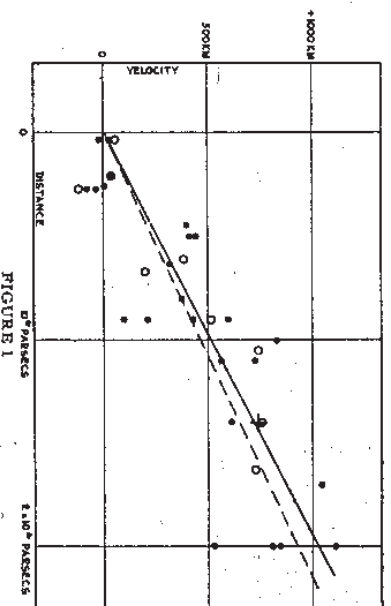


1923: Hubble Starts Measurements

1929: Publication of Distance Measurements

⇒ Galaxy Redshifts Increase Linearly  
With Distance from Earth!

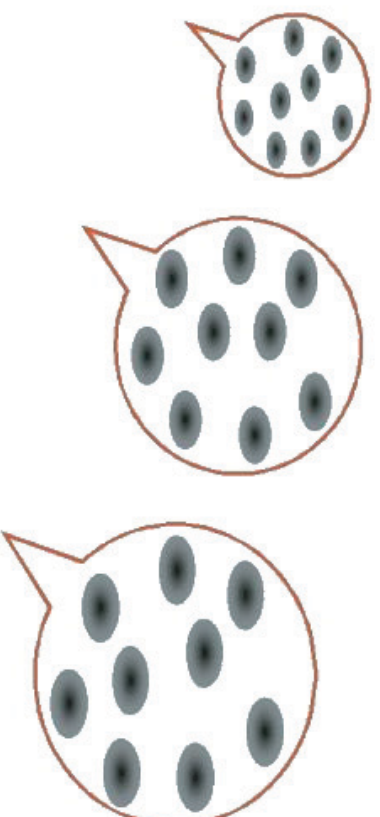
⇒ The Farther a Galaxy is Away from Us  
the Faster it Moves Away from Us



## The Expanding Universe...

Imagine a Balloon Filled With Galaxies...

Blow Up the Balloon...



Time Reverse: The Universe is Contracting!

⇒ Universe Gets Denser and Hotter

⇒ Primordial Fireball

⇒ **BIG BANG!**



**The big Bang**

10<sup>-43</sup> seconds  
10<sup>-34</sup> seconds  
10<sup>-10</sup> seconds  
10<sup>-5</sup> seconds  
3 minutes  
300 thousand years  
1 thousand million years  
15 thousand million years

10<sup>32</sup> degrees  
10<sup>27</sup> degrees  
10<sup>15</sup> degrees  
10<sup>10</sup> degrees  
10<sup>9</sup> degrees  
6000 degrees  
18 degrees  
3 degrees K

radiation  
particles  
heavy particles  
carrying the weak force  
quark  
anti-quark  
electron

positron (anti-electron)  
proton  
neutron  
meson  
hydrogen  
deuterium  
helium  
lithium

## Travel Back in Time and Space

## Traces of the Primordial Fireball?

Early Universe: Very Dense and Very Hot

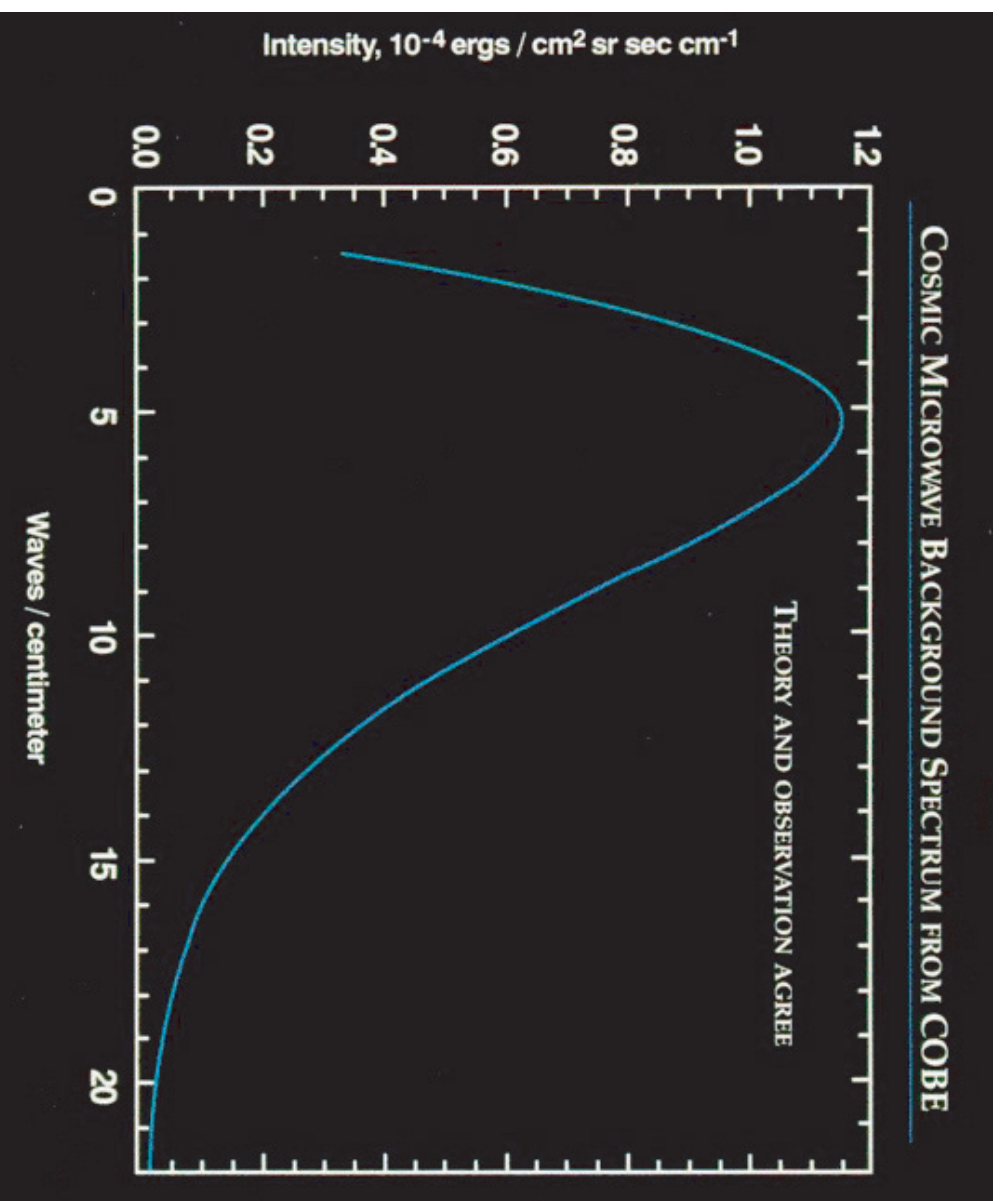
1946: Gamow Postulates Remnant Blackbody Radiation Left Over from Big Bang  $\approx 5K$

1965: Discovery of the Cosmic Microwave Background by Penzias and Wilson





## 2.725 K CMBR: The Perfect Black Body Radiation





## From CMB to Large Scale Structure

- Temperature Across the Sky Extremely Uniform
  - Present Day Universe **NOT** Uniform
- There must have been **Small Initial Fluctuations** ,  
which were Amplified by Gravity

Problems for Naive Big Bang:

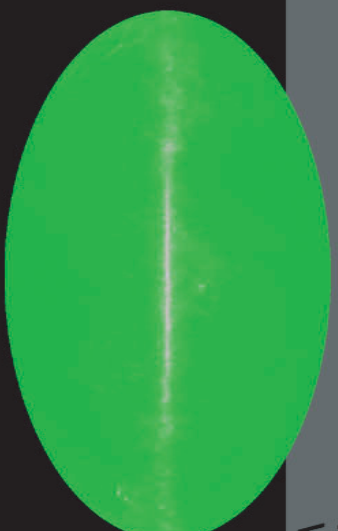
- Where do Initial Fluctuations Come from?
- Why did the Universe Not Collapse Immediately after the Big Bang?  
⇒ **Inflation**

# *The Cosmological Revolution*

1965



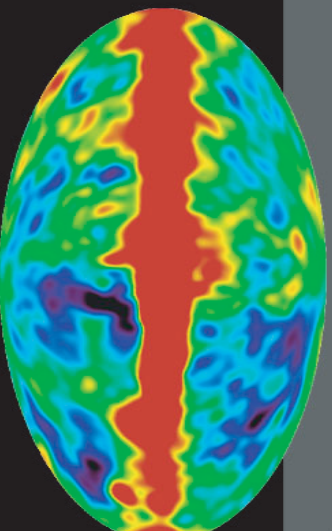
Penzias and  
Wilson



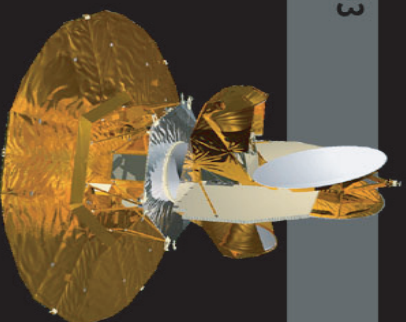
1992



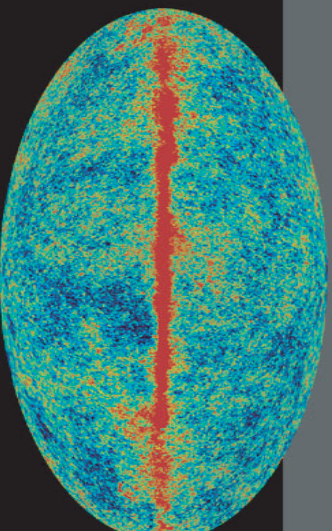
COBE



2003



WMAP



## What Can We Learn from CMB Observations?

- What are the Constituents of the Universe?

All **Baryons**?  $\Rightarrow$  Fluctuations Would be 10 - 100 Times Larger!

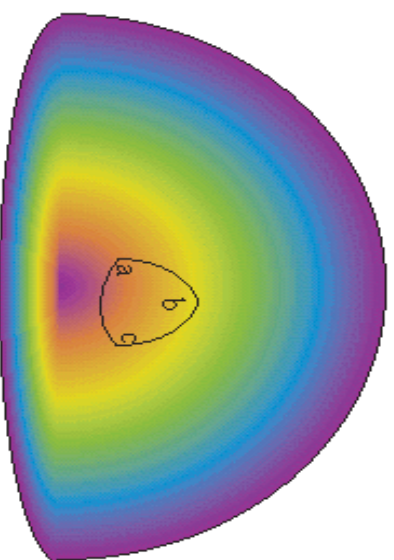
Need: Form of Energy which Interacts only **Gravitationally**

$\Rightarrow$  **Dark Matter!**

- What is the Geometry of the Universe?

# *The Cosmological Revolution*

Spherical space



$$a + b + c > 180$$

curvature = positive

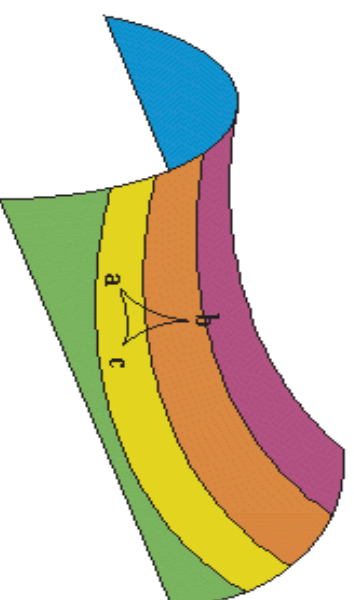
Flat Space



$$a + b + c = 180$$

curvature = 0

Hyperbolic space



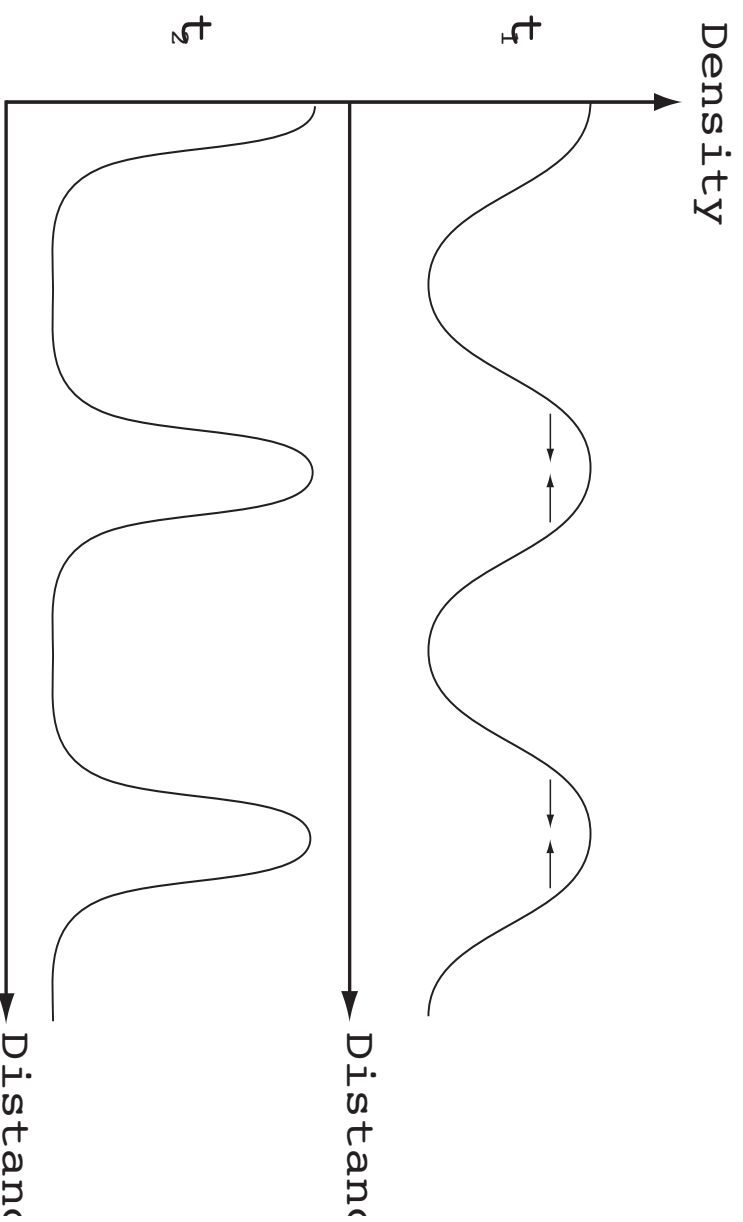
$$a + b + c < 180$$

curvature = negative

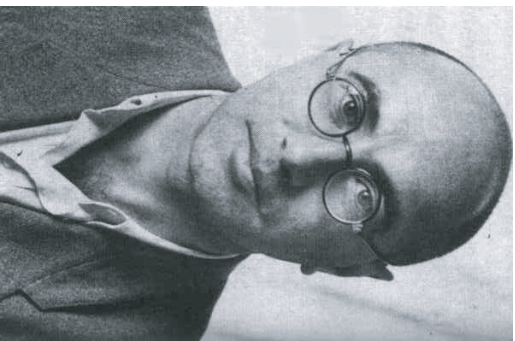
# The Geometry of the Universe - Measured by WMAP

## Formation of Large Scale Structure

- CMB Anisotropy is due to Small Fluctuations in Density
- Gravity is **Attractive!**



## Large Scale Structure Formation



Due to Nature of Gravitational Instability

⇒ Formation of Filaments and Pancakes  
Filaments Join up ⇒ Clusters Form

⇒ Formation of the Cosmic Web

Zel'dovich Develops Theory of  
the Formation of Large Scale Structure

Can We Test and Observe this?

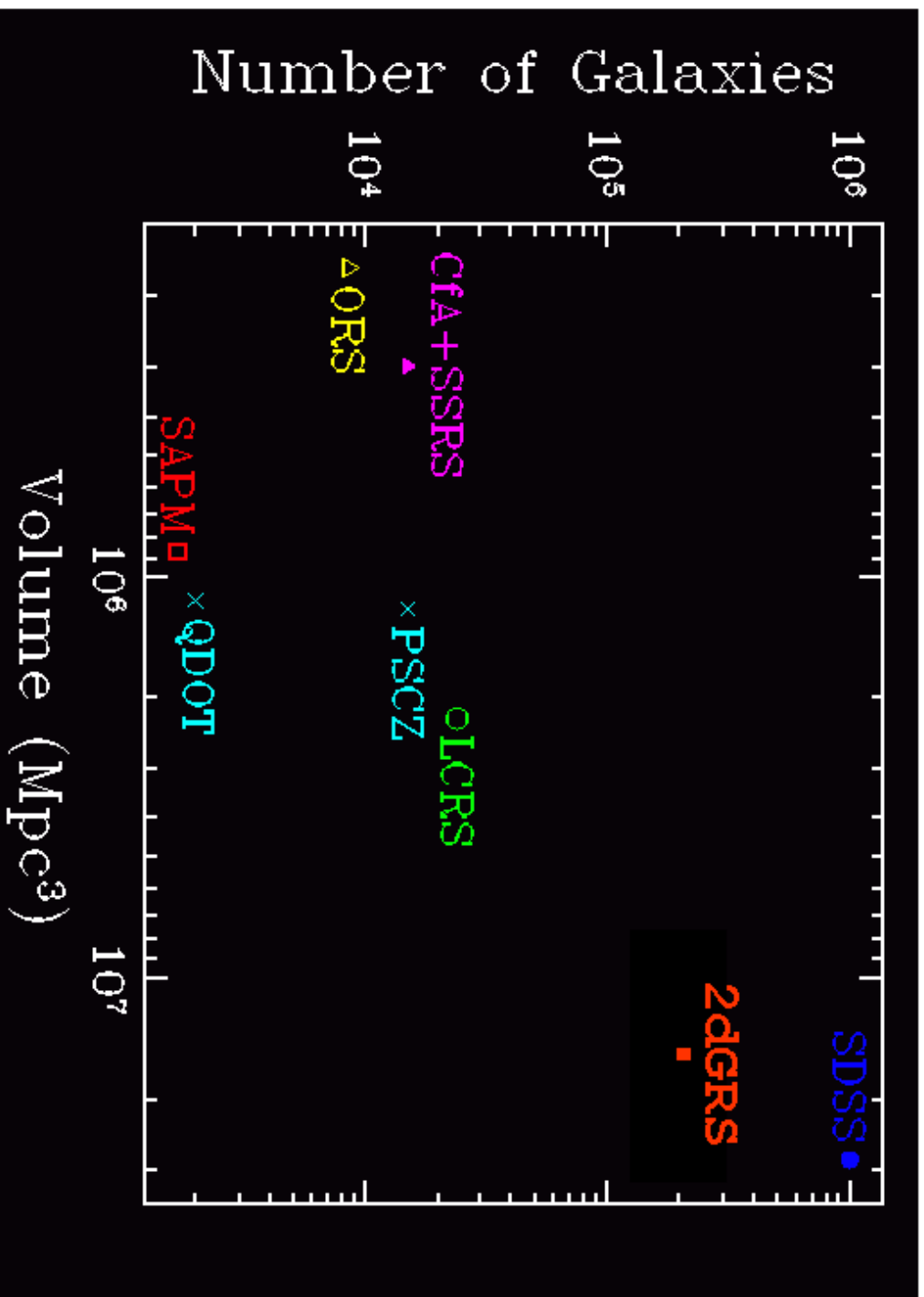
## The Cosmic Web



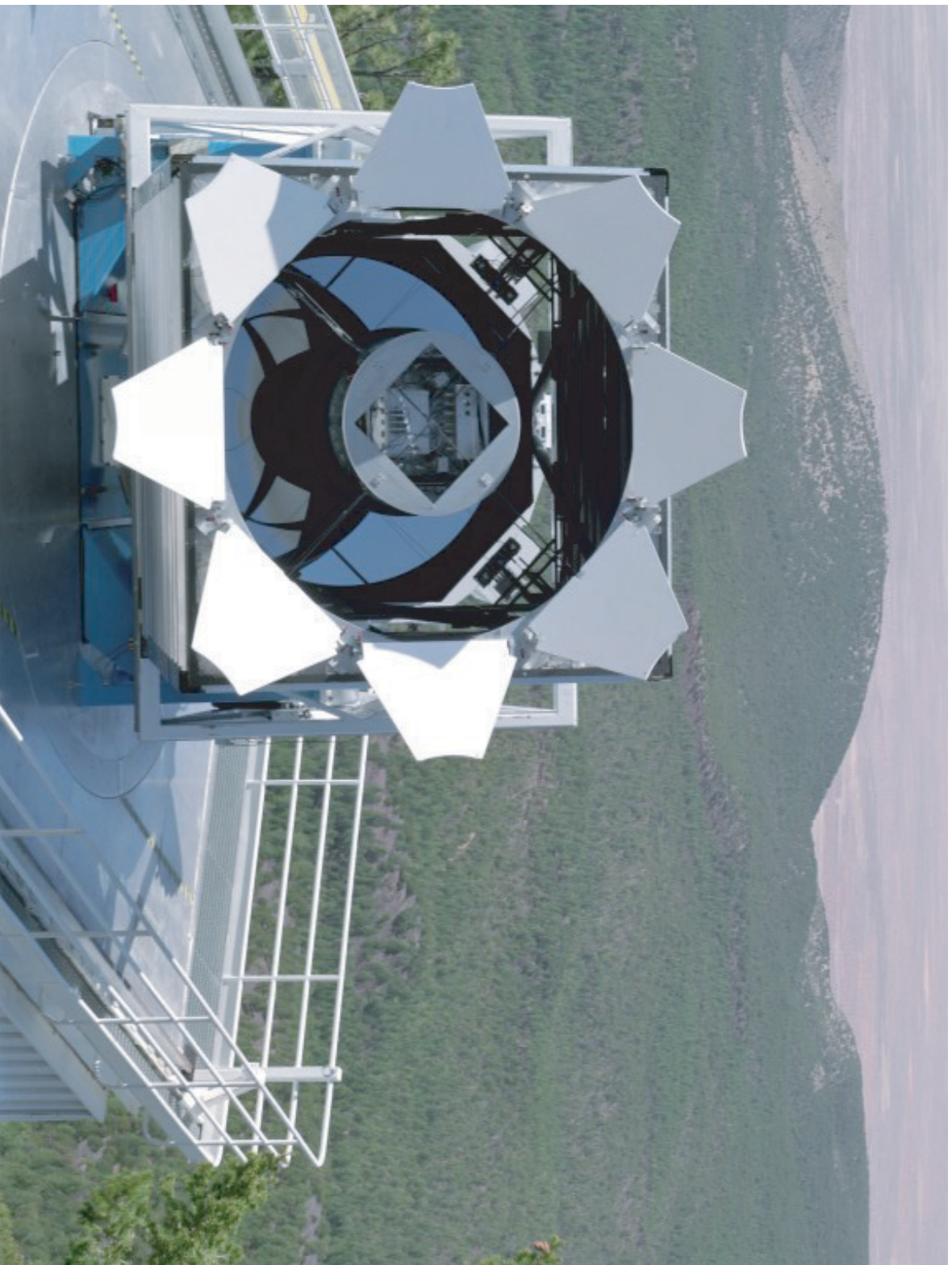
## A Cluster Simulation

## Large Scale Structure Surveys

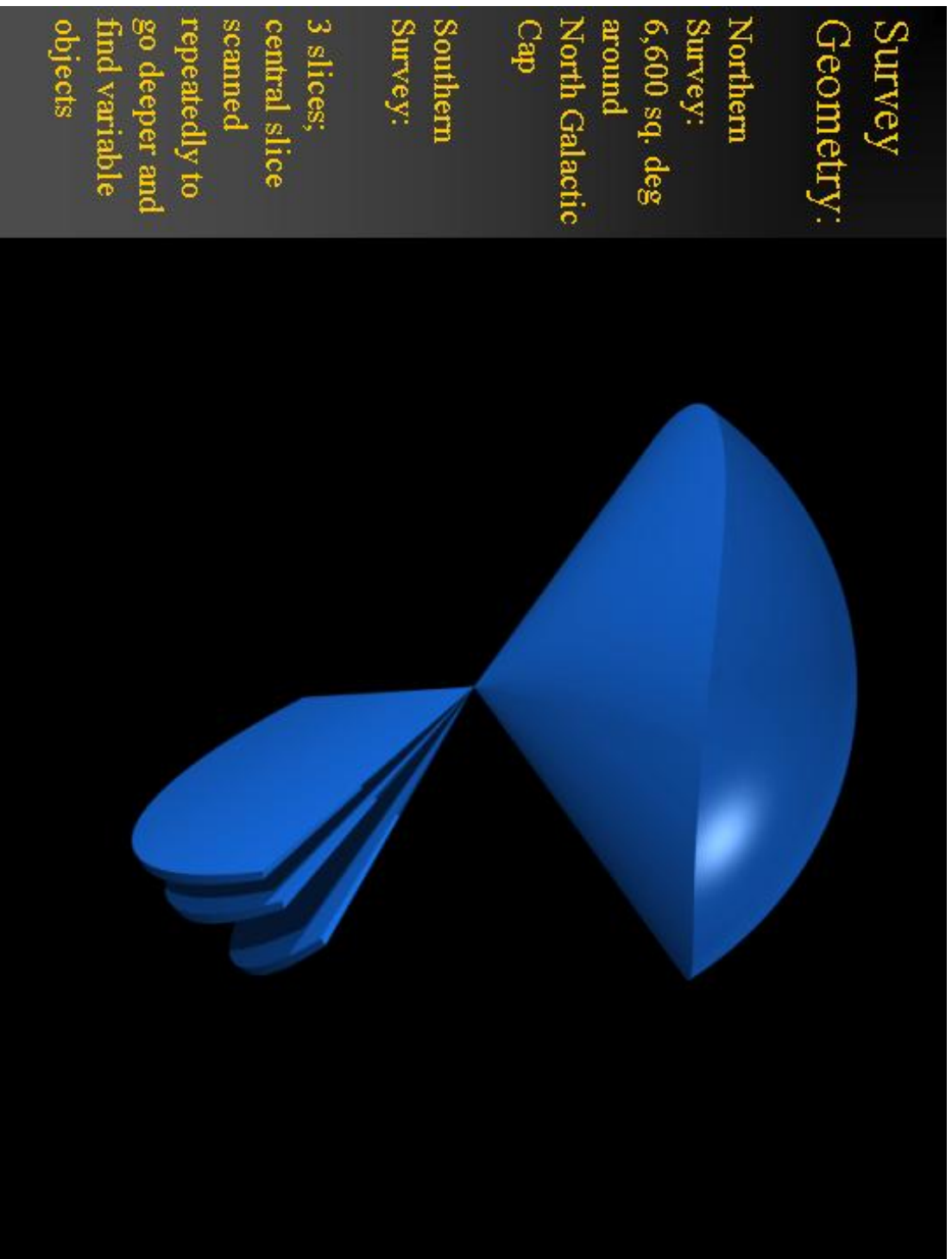
# Effective sizes of z-surveys



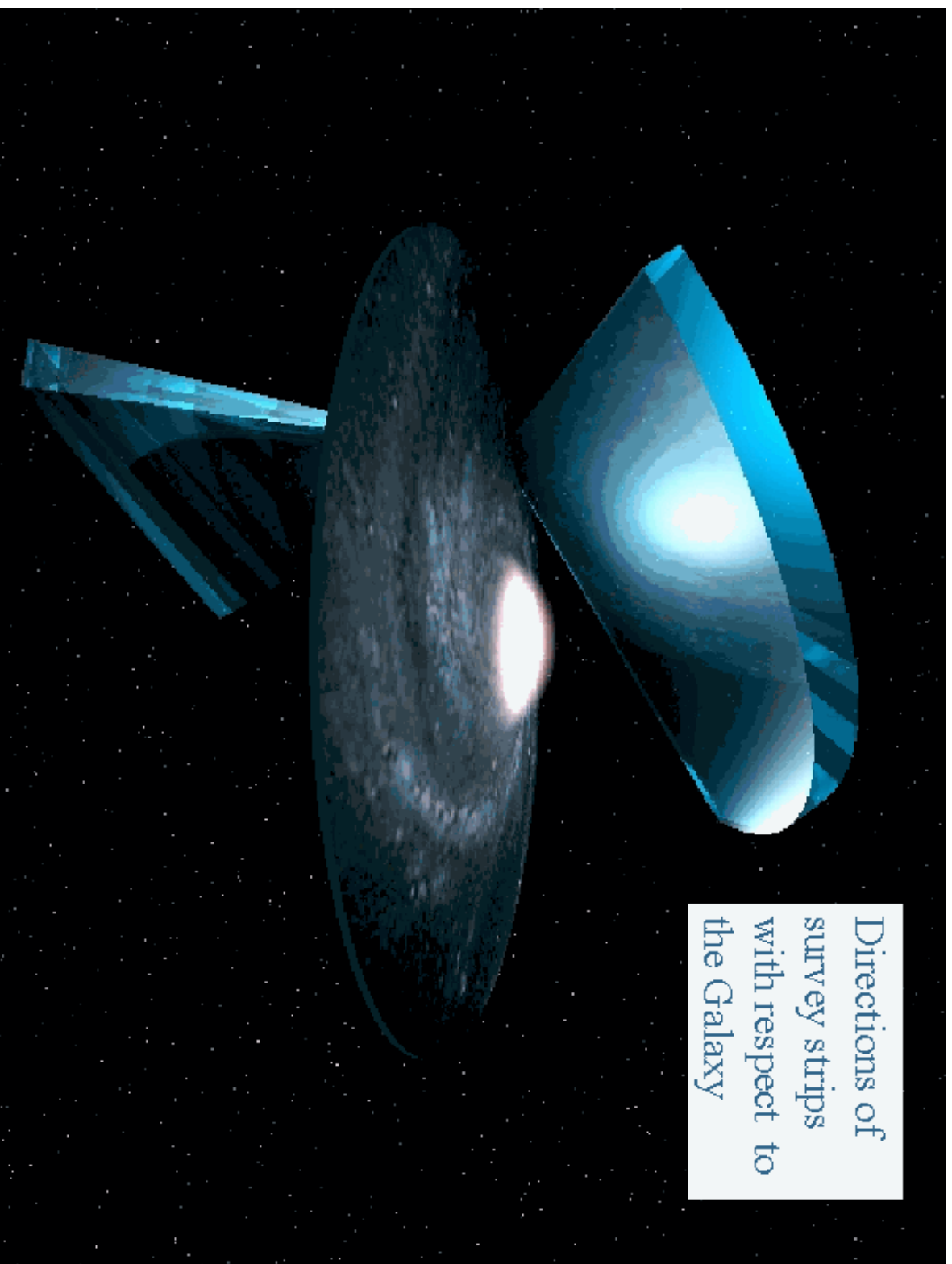
# *The Cosmological Revolution*



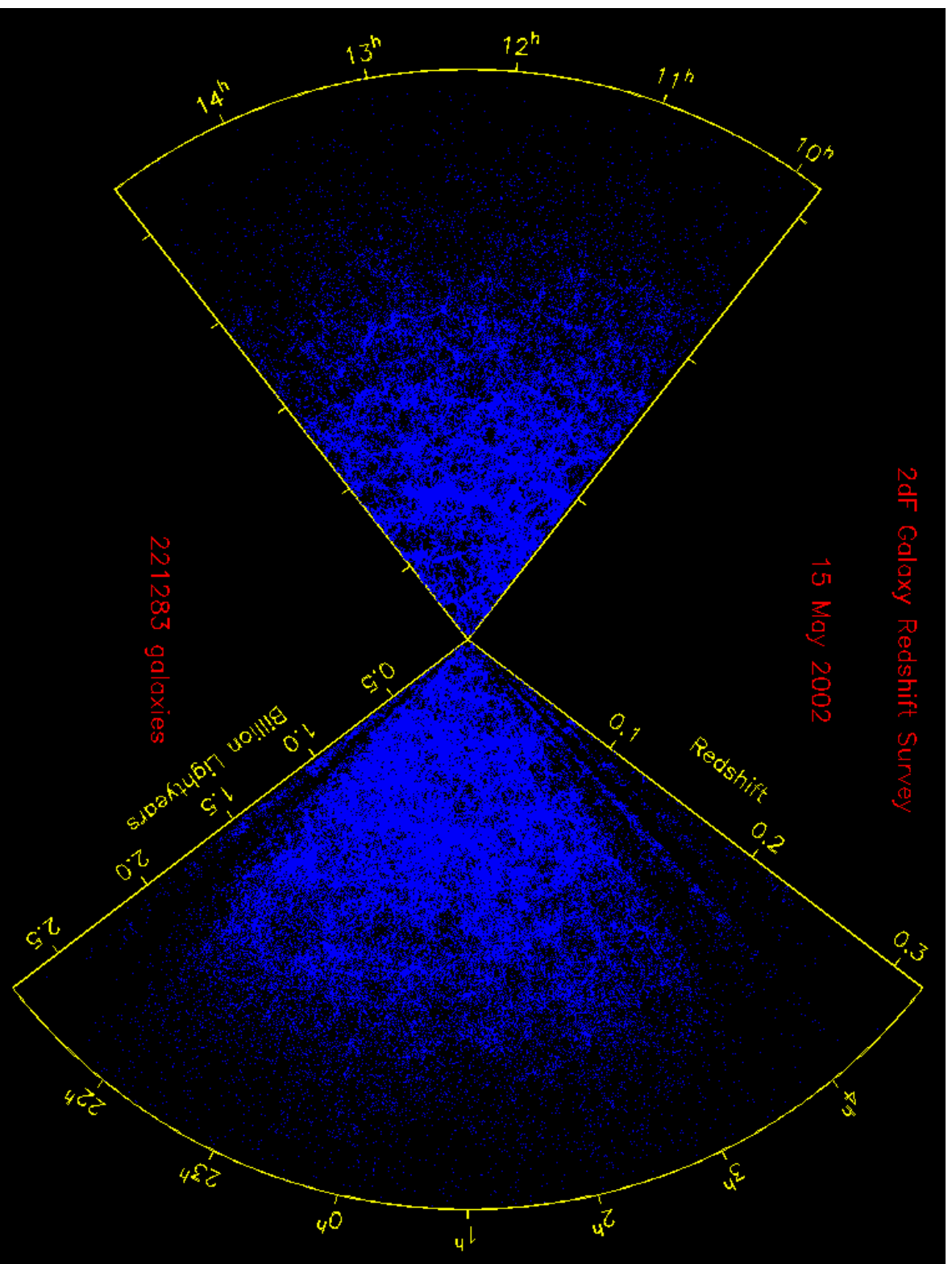
## The Sloan Digital Sky Survey



## *The Cosmological Revolution*



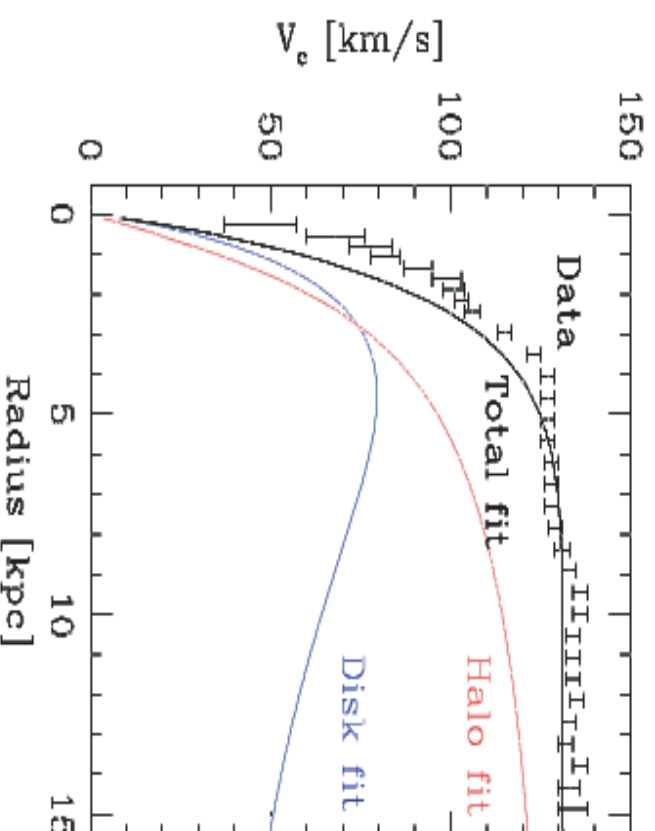
# *The Cosmological Revolution*



## Evidence for Dark Matter I: Rotation Curve

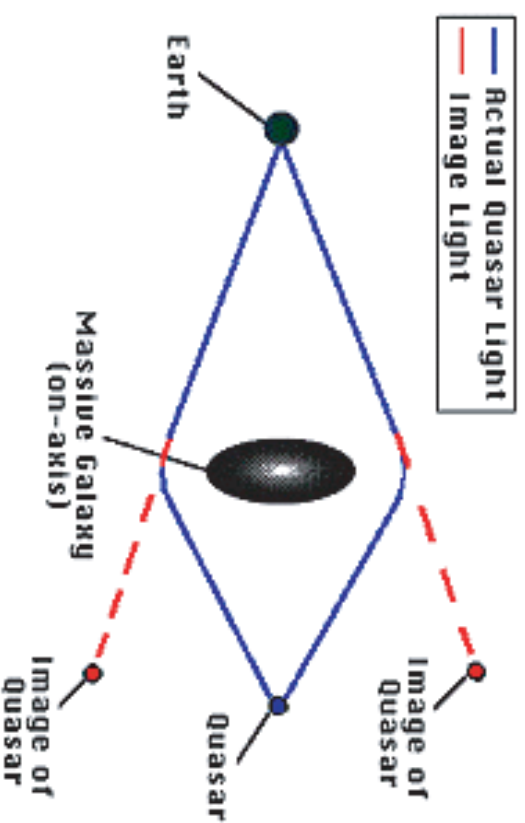
### Rotation Curve of a Disk Galaxy:

Plot of the Rotational Velocity  $v(r)$  of a Test Particle at a Distance  $r$  from the Center of a Distant Galaxy





## Evidence for Dark Matter II: Gravitational Lensing



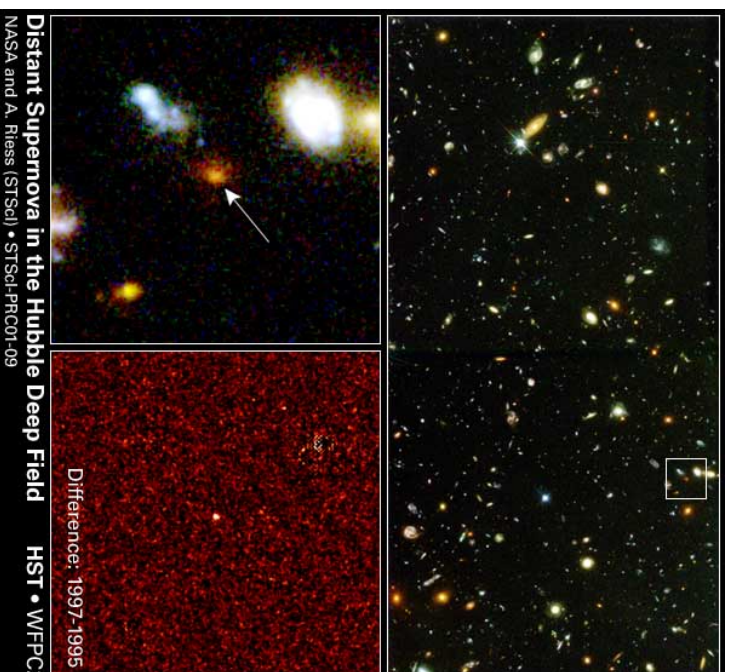


## Dark Matter Candidates

- Massive Compact Halo Objects (MACHOS)
- Weak Interacting Massive Particles (WIMPS)
  - WIMPZILLAS
  - Neutrinos
  - Black Holes
- Supersymmetric Particles
  - ...

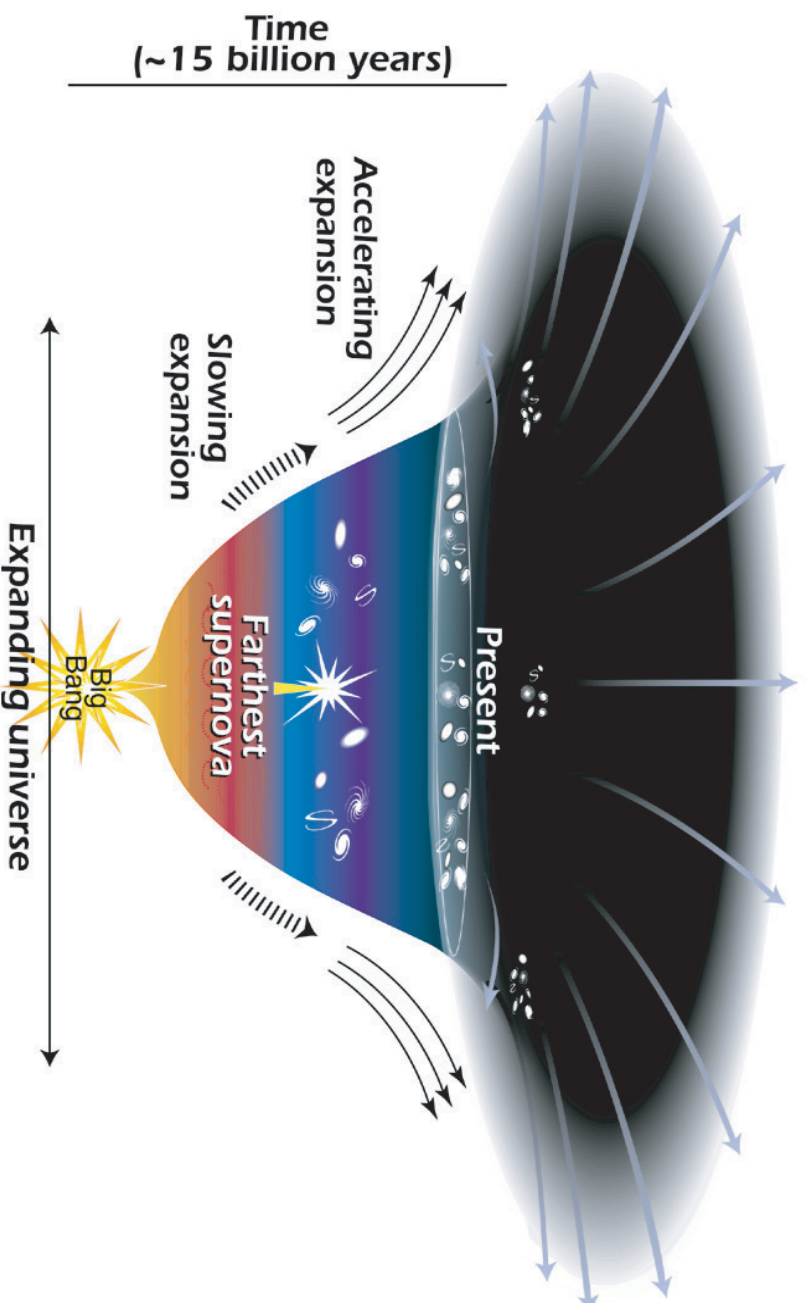
## The Dark Energy Puzzle

Type Ia Supernovae Appear **dimmer** than Expected  
from Constant Expansion Rate

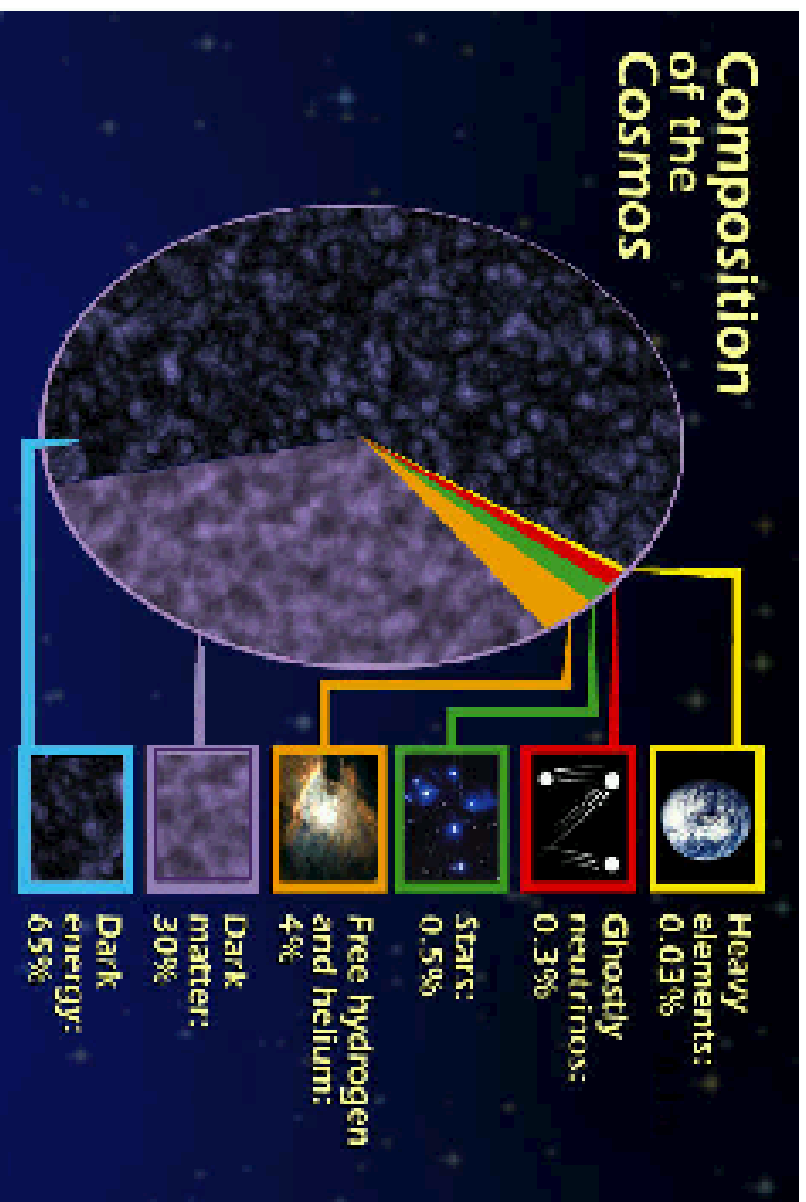


⇒ Dark Energy!

## Changes of the Rate of the Expansion over Time



## Our Current Picture of the Make-Up of the Universe





# The Future

## New and Ongoing Experiments

- Cosmic Microwave Background: Planck (2007)
- Supernovae: SNAP (2007)
- Galaxy Surveys: Sloan Digital Sky Survey (2005)

## Theoretical Questions

- Dark Energy
- Dark Matter
- Formation of Structure
- Formation of the First Stars